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Chemical Evolution of Elliptical Galaxies as a Constraint to Galaxy Formation Scenarios

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Abstract. Elliptical galaxies are the main contributors to the chemical enrichment of the intracluster and intergalactic medium; understanding how they form and evolve enables us to get important hints on the amounts of energy and processed matter that they eject into the ICM/IGM. Recent pieces of observational evidence point to a strong connection between high redshift quasars and their host galaxies. The aim of this paper is to prove that the main aspects of the chemical evolution of the spheroids can be reproduced in the framework of a model where the shining of the quasar is intimately related to the formation of the galactic nucleus. A key assumption is that the quasars shone in an inverted order with respect to the hierarchical one (i.e., stars and black holes in bigger dark halos formed before those in smaller ones) during an early episode of vigorous star formation. This scenario closely resembles the so-called ‘inverse wind’ model invoked to explain the observed increase of the [Mg/Fe] ratio in the nuclei of ellipticals with increasing the galactic mass, the only difference being that now the time for the occurrence of a galactic wind is not determined by the energy input from supernovae, but is indeed the energy injected by the quasar which regulates the onset of the wind phase.

1. Introduction

Most of the information on elliptical galaxies comes from their integrated properties: by analyzing colors and spectra by means of population synthesis techniques (e.g., Buzzoni et al. 1992; Bruzual & Charlot 1993; Bressan et al. 1994, 1996; Tantalo et al. 1998) one can infer the real abundances of the dominant stellar populations. A value of the elemental ratio $[\text{Mg}/\text{Fe}] > 0$ in the nuclei of ellipticals has been derived; moreover, $[\text{Mg}/\text{Fe}]$ has been found to increase with increasing

the galactic mass (Faber et al. 1992; Worthey et al. 1992; Weiss et al. 1995). The overabundance of [Mg/Fe] with respect to solar is generally interpreted as due to a short and intense star formation, perhaps coupled to an IMF slightly biased towards massive stars. Other observational hints favoring a scenario in which the bulk of the stellar population is build up on a short timescale are the existence of a tight fundamental plane (FP) in the 3-space of the basic global parameters central velocity dispersion σ , effective radius r_e , and mean effective surface brightness I_e (Bender et al. 1992; Renzini & Ciotti 1993) and the tight color- σ and color-magnitude relations (Bower et al. 1992) for ellipticals in local clusters, and the modest shift with redshift in the zero-point of the FP, Mg_2 - σ , and color-magnitude relations of cluster ellipticals at intermediate z (Dickinson 1995; Ellis et al. 1997; Bender et al. 1998; van Dokkum et al. 1998; Kodama et al. 1998; Stanford et al. 1998). A maximum age difference of ~ 1 Gyr between the bulk of the stellar population in field and cluster ellipticals at given mass has been inferred (Bernardi et al. 1998; see also Concannon et al. 2000 and Maraston & Thomas 2000), thus suggesting that most stars in ellipticals formed at $z > 3$, independently on the environment. The present day Type Ia and II SN rates in early-type galaxies ($Rate_{SNIa} = 0.18 \pm 0.06$ SNU, $Rate_{SNII} < 0.02$ SNU for $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$; Cappellaro et al. 1999) are another argument in favor of a scenario where a long-lasting phase of passive evolution follows an early episode of vigorous star formation. In fact, since Type II SNe come from short-living progenitors whereas Type Ia SNe come from long-living ones, the observed Type Ia and II SN rates imply that star formation in early-type galaxies must be nearly inactive at the present time.

In recent years, a strong connection between quasi-stellar objects (QSOs) observed at high redshifts and their host proto-galaxies has become apparent. In particular, the correlation between the central massive dark object and the hot stellar component of nearby galaxies (e.g., Kormendy & Richstone 1995; Magorrian et al. 1998; van der Marel 1999; Ferrarese & Merritt 2000; Gebhardt et al. 2000) suggests a direct connection between QSO activity and galaxy formation. Several models taking into account jointly the cosmological formation of QSOs and spheroids have appeared in the literature (Silk & Rees 1998; Friaça & Terlevich 1998; Monaco et al. 2000; Granato et al. 2001, among others). Following Monaco et al. (2000) and Granato et al. (2001), the QSOs shine at the centers of the spheroids while a vigorous star formation is building up the bulk of the stellar population. As a consequence of this, the surrounding medium is ionized, the star formation stops and a galactic wind develops. The QSOs shine in an *inverted hierarchical order* (Monaco et al. 2000), i.e., more massive spheroids experience the shining of the QSO before less massive ones. This scenario closely resembles the ‘inverse wind’ scenario invoked to explain the increase of the [Mg/Fe] ratio of the stellar populations in the nuclei of ellipticals with increasing total galactic luminosity (Matteucci 1994). We will show that by adopting the QSO shining times given by Monaco et al. (2000) and Granato et al. (2001) we can account for the main chemical properties of the stellar populations in early-type galaxies, thus giving further support to their model, which already reproduces: i) the evolution of the quasar luminosity function, ii) the 850 and 450 μm source counts together with their related statistics, iii) the mass function of dormant black holes in nearby galaxies and iv) the correlation of the black hole mass with the mass of the host galaxy spheroid.

2. The Model

Elliptical galaxies are considered initially as spheres of gas with luminous mass in the range $M_{gas} \sim 1.0 \times 10^{10} - 2.5 \times 10^{12} M_{\odot}$ embedded in a massive dark halo of mass $M \sim 7 M_{gas}$. At the beginning, both baryonic and dark matter follow a Navarro, Frenk, & White (1997) density profile. Then, baryonic matter cools, collapses and starts forming stars. We assume a single zone interstellar medium (ISM) with instantaneous mixing of gas throughout. The star formation builds up the bulk of the stellar population with high efficiency in a short timescale. Then, the QSO shines at the centre, ionizes the ISM and stops the star formation. A galactic wind eventually develops at this stage. The shining times, t_{QSO} , are listed in Table 1 as a function of the initial gaseous mass. We compute the cooling time and the dynamical time at each radius and define r_{cool} , the maximum radius at which both the cooling time and the dynamical time are still lower than t_{QSO} . Obviously, only matter inside r_{cool} (a fraction α of the initial gaseous mass) will enter the process of star formation. The quantity α is listed in Table 1.

The star formation rate (SFR) is given by:

$$\psi(t) = \nu M_{cold}(t), \quad (1)$$

where $M_{cold}(t)$ is the gas mass which has cooled by the time t . The quantity ν , expressed in units of Gyr^{-1} , represents the efficiency of star formation, namely the inverse of the timescale of star formation. The timescale of star formation is the maximum between the mean values of the cooling time and the dynamical time inside r_{cool} .

The fundamental equations of chemical evolution, which allow us to follow the temporal evolution of the abundances of several elemental species in the gas are:

$$\frac{dG_i(t)}{dt} = -X_i(t)\psi(t) + R_i(t) + \left(\frac{dG_i}{dt}\right)_{infall} - \left(\frac{dG_i}{dt}\right)_{reheat}. \quad (2)$$

$G_i(t) = X_i(t)M_{cold}(t)$ is the cold gas mass in form of the element i ; $X_i(t)$ is the abundance by mass of the element i ; $R_i(t)$ is the rate at which dying stars eject both processed and unprocessed matter (see Matteucci & Greggio 1986). The last two terms on the right account for the accretion of cold gas by infall and for the reheating due to supernova explosions, namely the rate at which the gas is heated by SNe and therefore subtracted to star formation.

As far as the initial mass function (IMF) is concerned, we choose either a Salpeter IMF, $\phi(M) \propto M^{-1.35}$, or $\phi(M) \propto M^{-1.15}$. The normalization is performed in the mass range 0.1–100 M_{\odot} .

The average abundances of the composite stellar populations we use are the mass-averaged ones, namely:

$$\langle X_i \rangle = \frac{1}{S_{tot}} \int_0^{S_{tot}} X_i(S) dS, \quad (3)$$

where S_{tot} is the total mass of stars ever born.

Table 1. Model parameters [columns from (2) to (5)] together with some model results [columns from (6) to (9)]. See text for details.

Model (1)	M_{gas} (2)	t_{QSO} (3)	α (4)	ν (5)	M_{stars} (6)	$\langle[Mg/Fe]\rangle$ (7)	Mg_2 (8)	$\langle Fe \rangle$ (9)
1	2.5×10^{12}	0.6	0.15	4.8	2.7×10^{11}	0.443	0.246	2.614 ^a
					2.9×10^{11}	0.550	0.310	2.982 ^b
2	9.5×10^{11}	0.7	0.20	4.3	1.6×10^{11}	0.424	0.249	2.658 ^a
					1.7×10^{11}	0.537	0.314	3.016 ^b
3	5.5×10^{10}	1.6	0.70	1.5	2.4×10^{10}	0.333	0.227	2.561 ^a
					2.3×10^{10}	0.471	0.280	2.838 ^b
4	2.0×10^{10}	2.1	0.90	1.1	8.0×10^9	0.288	0.209	2.456 ^a
					6.9×10^9	0.438	0.253	2.670 ^b
5	1.0×10^{10}	2.5	1.00	1.0	3.5×10^9	0.249	0.193	2.348 ^a
					2.8×10^9	0.410	0.228	2.507 ^b

^a $\phi(M) \propto M^{-1.35}$; ^b $\phi(M) \propto M^{-1.15}$

3. Model results and discussion

In Table 1 we report model parameters [column (2): initial gaseous mass, in units of M_\odot ; column (3): QSO shining time, in units of Gyr; column (4): fraction of M_{gas} which cools and collapses before t_{QSO} ; column (5): star formation efficiency, in units of Gyr^{-1}] and results [columns (6): mass converted into stars from $t = 0$ to $t = t_{QSO}$, in units of M_\odot ; column (7): average $[Mg/Fe]$ of the composite stellar population at $t = t_{QSO}$; columns (8) and (9): metallicity indices Mg_2 and $\langle Fe \rangle$ of the composite stellar population at $t = t_{QSO}$]. Results for both $\phi(M) \propto M^{-1.35}$ and $\phi(M) \propto M^{-1.15}$ are shown for each model galaxy.

Owing to the fact that the QSOs in more massive host proto-galaxies shine before those in less massive ones, larger $\langle[Mg/Fe]\rangle$ ratios are displayed by the stellar populations of more massive spheroids, in agreement with observations. In fact, a prolonged star formation period results in adding younger stellar components formed out of iron-enriched gas, due to the temporal delay in type Ia SN explosions which restore the bulk of iron (e.g., Matteucci 1994). Moreover, at the time of the shining of the QSO, all our massive galaxies have reached a roughly solar or even super-solar metallicity at the center, in agreement with observational hints on the metal content in QSO environments (Hamann & Ferland 1999). The theoretical $\langle[Mg/Fe]\rangle$, $\langle[Fe/H]\rangle$ ratios can be converted into metallicity indices following the prescriptions by Matteucci et al. (1998) to be compared to observations in the Mg_2 – $\langle Fe \rangle$ diagram. We want to stress that introducing a reheating term in Eq.(2) helps us in reproducing the observed range of definition of the Mg_2 index (see Fig.1). However, at present we used a very simplified treatment for the SN feedback, taking into account only type II SNe.

Recently, Trager et al. (2000) derived values of the $\langle[E/Fe]\rangle$ and $\langle[Fe/H]\rangle$ ratios for a sample of ellipticals from a set of observed indices (E refers to

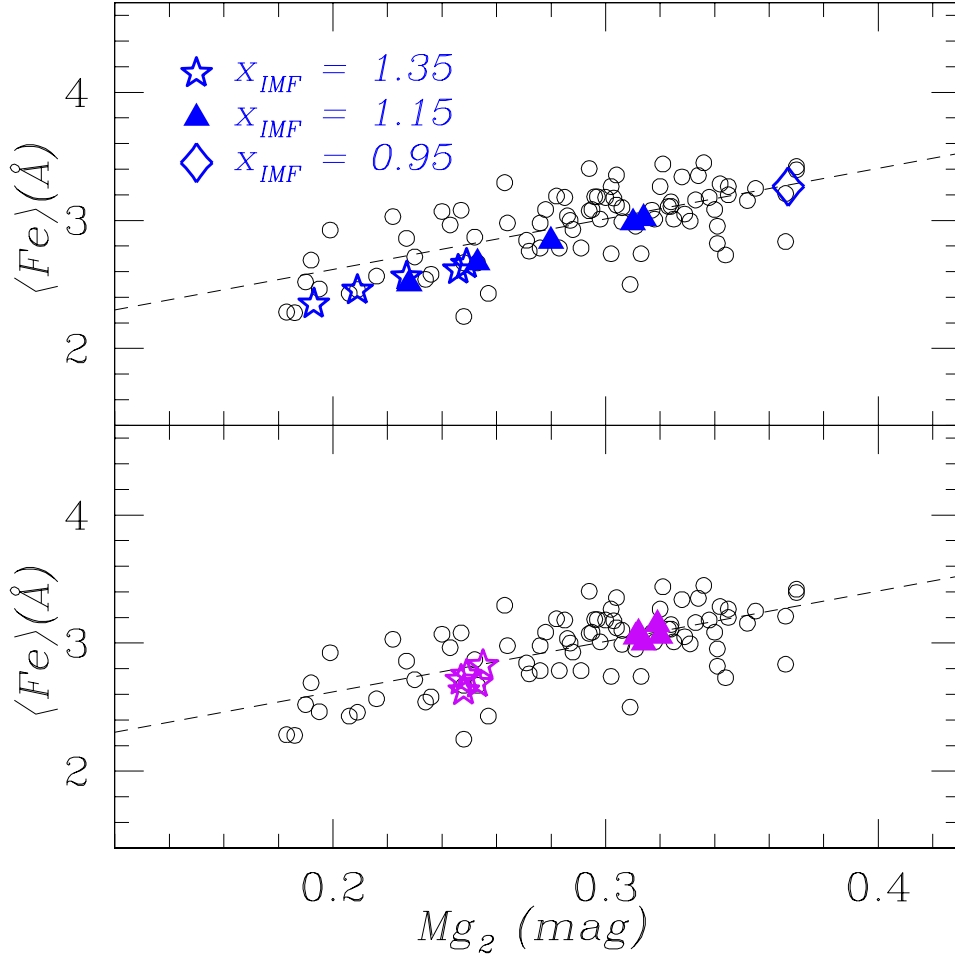


Figure 1. Mg_2 vs. $\langle Fe \rangle$ theoretical relations compared to the available data (*open circles*; Worthey et al. 1992; González 1993; Carollo & Danziger 1994a, b). Results relevant to $\phi(M) \propto M^{-1.35}$ (*stars*) and to $\phi(M) \propto M^{-1.15}$ (*triangles*) are shown for Models from 1 to 5. The same results are listed in Table 1. The big diamond refers to Model 1 computed with an even steeper IMF ($\phi(M) \propto M^{-0.95}$). Results in the top panel refer to models in which the reheating term [see Eq.(2)] is taken into account, whereas results in the bottom panel refer to models in which the reheating term is set to zero. We conclude that accounting for the reheating due to SN explosions helps us in reproducing the observed range of definition of the Mg_2 index.

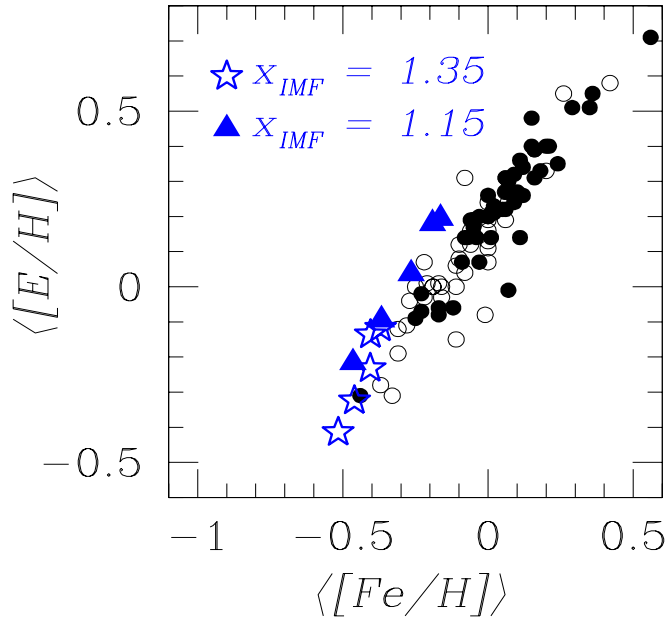


Figure 2. Theoretical $\langle [E/H] \rangle$ vs. $\langle [Fe/H] \rangle$ compared to the data from Trager et al. 2000 (see text for details).

all ‘enhanced’ species, see Trager et al.). In Fig.2 we compare our theoretical predictions to their data, relevant to both $r_e/8$ (*filled circles*) and $r_e/2$ (*open circles*). Since we adopt a one-zone model, our results should be considered as relevant to an aperture r_e . The agreement with the data is quite good. The interesting point is that we do not find the need for a significant young stellar component to be added to the older one in order to reproduce the data.

We have tested the coupled QSO-host galaxy formation scenario against the main chemical properties of the composite stellar populations of early-type galaxies and shown that they can indeed be reproduced, at least in the framework of the simple one-zone chemical evolution model described here. It has been recognised that SNe alone are unlikely to be the source of the overall IGM heating and need to be supplemented or even substituted by some other heating processes (Kravtsov & Yepes 2000 and refs. therein). Radiation from QSO population could provide the required heating (Valageas & Silk 1999). Therefore, further study should be deserved to the topic of the QSO-host galaxy connection.

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